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Global Advanced Reactor R&D

Global Nexus Initiative

January 9, 2018

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Outline

- Global Advanced Reactor R&D landscape
  - Russia
  - China
  - India
  - United States
  - France
  - Japan
  - Canada
  - Argentina
- CATF-EON energy model under development

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WORLD SUMMARY (1/2)

- Advanced nuclear R&D is led by state-funded efforts in Russia and China, followed by India. All three are either operating or commissioning large prototype or even commercial advanced nuclear units currently.
- While extensive R&D efforts are ongoing in South Korea, France, the US, Belgium and across the EU, no firm near-term construction plans are in place for advanced systems at present.
- A record number of nuclear "start-ups", most of which based in the US, are currently developing advanced designs, but most are at relatively low level of technical maturity.
- In non-LWR government programs, sodium-cooled fast reactors continue to dominate overall spending, followed by high-temperature gas reactors and lead-cooled fast reactors. In the significantly smaller privately-funded initiatives, many are focused on Molten Salts.

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WORLD SUMMARY (2/2)

- A new generation of Small Modular Light-Water Reactors are nearing commercial operation, with CAREM-25 in Argentina starting operation next year, Korea's licensed SMART reactor to be built in Saudi Arabia and the US NuScale reactor progressing through NRC licensing.
- All advanced non-LWR programs envision a shift in fuel technology away from the conventional uranium-oxide based fuels. China & India both plan to transition to metallic fuels for their future fast reactors, while Russia is exploring both metallic and nitride-based fuels.
- There is no developing global consensus on the ideal sizing of advanced Gen-IV nuclear plants. The Russian, Chinese and Indian fast reactor programs all have development paths leading to larger and larger reactors (all scaling from tens of MW to 1000+), while individual gas-cooled units remain small.
- Light water reactor development has diverged in to either extremely large units (1400-1700 MWe EPR, APR-1400, ESBWR etc.) or the SMR trend of very small units (40-200 MWe)

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RUSSIA – SUMMARY

THE BN-800 REACTOR IN BELOYARSK NEAR YEKATERINBURG) IN RUSSIA

- Most of Russian advanced nuclear R&D falls within the very comprehensive Proryv (Breakthrough) project.
- Proryv includes the development & construction of both a new large commercial sodium reactor (BN-1200) and a smaller prototype lead-cooled reactor (BREST-OD-300), and a multitude of supporting facilities including advanced nitride fuel fabrication and reprocessing plants.
- To support overall advanced nuclear R&D, Russia is also building a new materials testing reactor (the MBIR)
- Russia has two large commercial fast reactors in operation (BN-600 & BN-800) at Beloyarsk, making them the undisputed world leader in fast reactor technology, and fast reactors remain their main focus.
- Russia is also focusing specifically on sea-based LWR SMRs, expanding the use of their nuclear ice-breaker technology base to sea-mobile power production facilties.

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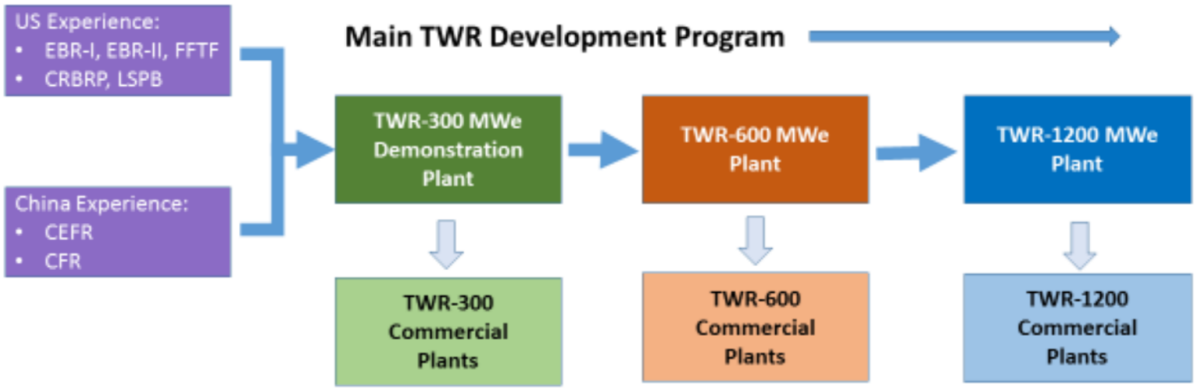
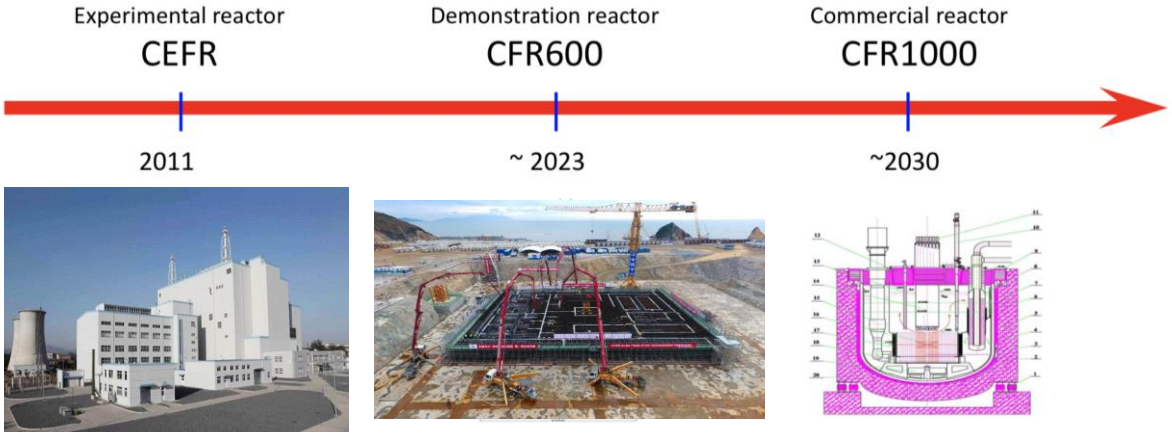
CHINA – SUMMARY (1 of 2)

- China is simultaneously running serious R&D programs for essentially all major types of advanced nuclear, including sodium and lead-cooled fast reactors, molten salt reactors and high temperature gas reactors.





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CHINA – SUMMARY (2 of 2)

- In terms of budget, the main focus is on the gas and sodium-cooled programs. The gas-cooled program is currently commissioning a commercial prototype plant (the 210 MWe HTR-PM), while construction has started of a large sodium-cooled fast reactor (the 600 MWe CFR-600).
- Concurrently, China is commercializing multi-use LWR SMR designs such as the Linglong One (ACP100), with construction start of the first unit imminent.

GRAPHITE PEBBLES (MODERATOR) BEING LOADED AT HTR-PM, APRIL 2017

HTR-PM VESSEL HEAD INSTALLED, DECEMBER 2017

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INDIA – SUMMARY

- India continues to follow it's "3-step" nuclear program, the ultimate aim of which is to make use of its indigenous resources of Thorium.
- For near-term power production, India is focusing on the continued construction of pressurised heavy water reactors (PHWR), while R&D is focused on sodium cooled fast reactors specifically.
- The main development project is the 500 MWe Prototype Fast Breeder Reactor (PFBR), a commercial prototype sodium cooled fast reactor.
- Construction of the PFBR finished early in 2017 and the unit will enter operation this year.

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INDIA – Prototype Fast Breeder Reactor

THE PFBR REACTOR AT KALPAKKAM, INDIA

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United States - SUMMARY

- The US does not have a nationally coordinated advanced reactor development program, but rather a large number of smaller R&D projects carried out mainly at national laboratories (in collaboration with academia/industry). Over the last 18 years, the DOE has spent a total of about $2 billion on advanced (non-light water) reactor research, 4% of DOE's total energy R&D expenditure.
- The most serious and well-funded (also with Gov't support) R&D efforts aimed at construction and operation of new advanced nuclear technology are privately led initiates such as TerraPower (sodium and molten salt reactors), GE-Hitachi PRISM (sodium-cooled), NuScale (small PWRs), X-Energy (gas-cooled high. Temp reactor), and a very large number of smaller start-ups, many of which focus on Molten Salt systems.
- The recently launched GAIN program enables support and private industry use of government R&D facilities, which may greatly speed up development efforts for advanced nuclear.

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FRANCE – SUMMARY

- The main advanced nuclear R&D program of France is focused on the development of sodium cooled fast reactors within the ASTRID program.
- The ASTRID project employs around 600 people and is led by the CEA in collaboration with 13 industrial partners. The "basic design phase" ends in 2019, when the final decision to proceed to construction will have to be taken.
- While France and the CEA is involved in nearly all of European advanced nuclear R&D projects, the ASTRID project dominates its efforts and funding.

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JAPAN – SUMMARY

- Japanese advanced nuclear R&D continues but faces an uncertain future following the Fukushima events.
- The historical focus has been two-pronged: sodium fast reactors and high temp. gas reactors.
- It has been decided that the country's main fast reactor R&D facility, the MONJU reactor, will be decommissioned. A smaller facility containing the JOYU reactor is applying for permission to re-start and carry on operations.
- The HTTR, Japan's world-leading* high-temperature gas-cooled reactor, is currently undergoing safety review by the regulator. It is expected to return to operation.

*About to be over-taken by Chinas larger HTR-PM system due to be operational this year

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CANADA – SUMMARY

- In recent years Canada has become the preferred target market for a large number of advanced nuclear designs. Reasons include an experienced and well-structured nuclear regulator and regulatory system and the availability of niche-market applications such as arctic communities and mining.
- Canadian company Terrestrial Energy is a frontrunner in the development of Molten Salt Reactors, and has recently completed the first phase of the vendor design review by the Canadian regulator (an advanced nuclear first).
- Canadas government-led R&D efforts remain primarily focused on the indigenous CANDU technology.

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ARGENTINA – SUMMARY

- Argentina is a world-leader in Small Modular Reactor (SMR) development, with the CAREM reactor program currently having reached the farthest out of any SMR program worldwide.
- The CAREM-25 nuclear reactor, nearing construction completion and due to be in operation next year, is a modular 100 MWt simplified pressurised water reactor with integral steam generators, designed to be used for electricity generation (25 MWe net) or for water desalination.
- The CAREM-25 prototype will be followed by a larger version, 100 MWe or possibly 200 MWe, in the northern Formosa province by 2021.

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CATF-EON Simplified World Energy System Model

The model should allow the user to explore the effects of a broader range of:

- Population growth rates
- Fuel costs
- Energy intensities
- Economic growth rates
- PV costs
- Nuclear Power costs
- NGCC costs

Questions the initial version of the model needs to help answer:

- Market for advanced nuclear at different various capital costs/coe
- Extent of PV penetration if storage is too expensive
- COE in different regions over time
- Reasonable ranges for energy demand

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Model Basis and Outputs

- Regions will match IEA regions
- For each region, population, economic growth, and energy intensity will be calculated, starting from an IEA WEO baseline scenario.
- These would produce annual estimates of energy use by sector for the region.
- The model will use UN statistics for population projections.

Outputs in table and chart form:

- New capacity additions, by region
- MWh additions by region
- Installed capacity by generation type
- Carbon emissions by sector
- Potential market size for a new technology based on capital cost and coe.

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About the Nuclear Innovation Alliance

The NIA is a cross-cutting organization with an advisory board drawing from advanced reactor designers, industry, academia, NGOs and environmental organizations.

We support advanced nuclear energy innovation.

- ***We assemble companies, investors, experts, and stakeholders to advance nuclear energy innovation and enable innovative reactor commercialization through favorable energy policy and funding.***
- ***We research, develop, and advocate policies that enable the efficient licensing and timely early-stage demonstration of advanced reactor technologies.***

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www.nuclearinnovationalliance.org

Backup Slides

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Russia - Details

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RUSSIA – FAST REACTORS

Russia is currently running three concurrent fast reactor development programs:

1. The BN program (sodium-cooled fast reactors)
2. The BREST program (lead-based fast reactors)
3. The SVBR program (lead-based fast reactors)

These are supported by the development of the **MBIR** R&D reactor facility.

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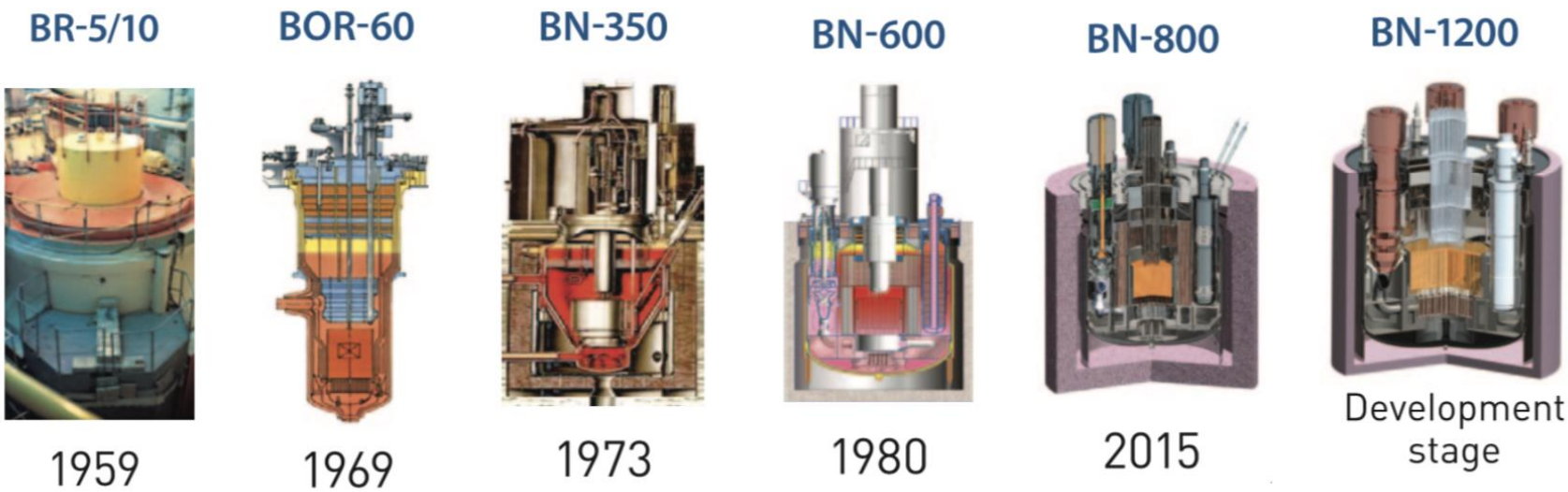
RUSSIA – BN-SERIES REACTORS

- The Russian BN-series of reactors is the most advanced and commercially successful fast reactors in the world to date.
- The 600 MWe BN-600 has been in commercial operation since 1980, its larger 800 MWe sister BN-800 has now completed its first year of grid-connected operation.
- The BN-1200, still in development, is meant to be the reference fast reactor and cost-competitive with LWRs in Russia.



RUSSIA – BN-600

- The BN-600 sodium-cooled fast reactor has achieved an average 75% load factor over 30 years of commercial, grid-connected operation, with its best ever years being the last three.
- There is little reason why the BN-600 would not qualify as an "advanced" reactor or even (depending on definition) a "Gen-IV system." It is active proof-of-concept of the commercial viability of fast reactor systems.
- The BN-600 continues to be both a commercial power producer and a basis for R&D supporting the development of future Russian SFRs.

BN-600 REACTOR HALL

BELOYARSK NPP (BN-600)

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RUSSIA – BN-800 & BN-1200

- The 800 MWe sodium cooled fast reactor BN-800 reached initial criticality in 2014 and entered full commercial operation in November 2016, it is now the largest advanced reactor in operation in the world (second largest in history after the French Super-Phenix).

THE BN-800 REACTOR IN BELOYARSK NEAR YEKATERINBURG) IN RUSSIA

- The aim of the BN-reactor series is a step-wise approach toward a final commercial design called BN-1200. The BN-1200 has been in development for many years, but it is envisioned that the design will be further improved by the operational experience of the BN-800 reactor.

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RUSSIA – PRORYV and BREST

- As part of the Proryv (Breakthrough) project, Russia is building a pilot energy complex at the site of the Siberian Chemical Combine in the Tomsk region. It comprises a fuel production plant; a nuclear power plant with a BREST-OD-300 lead cooled fast reactor reactor; and a used fuel retreatment module.
- Following the BREST-300 demonstration plant, the development program is focused toward a very large (1200 MWe) lead-cooled nitride-fuelled reactor (BR-1200). A requirement for the BR-1200 is that capital costs should be $2300/kW, or at least 20% lower than for VVER-TOI (the modern Russian PWR)
- The construction of a fuel fabrication module for dense nitride fuel in support of Proryv and the BN-reactors begun in 2015 and is scheduled for completion in 2020.

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RUSSIA – THE MBIR

- MBIR will be a multi-loop research reactor capable of testing lead, lead-bismuth and gas coolants, and running on MOX (mixed uranium and plutonium oxide) fuel..
- The facility is currently under construction at the site of the Research Institute of Atomic Reactors (NIIAR) at Dmitrovgrad
- NIIAR intends to set up on-site closed fuel cycle facilities for the MBIR, using pyrochemical reprocessing it has developed at pilot scale
- Construction of the MBIR is scheduled for completion by 2020.
- MBIR is inviting international organisations to partner and make use of its capabilities.

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US - Details

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United States – NuScale SMR

- NuScale is a US-developed 50 MWe (gross) PWR SMR reactor system. Up to 12 NuScale units can be controlled from a single control room. NuScale has emerged as the clear front-runner among the US SMR concepts, and is highly likely to be the first SMR to go through the full US NRC regulator licensing approval process.
- The UAMPS Carbon-Free Power Project, a 12-module Nuscale SMR plant owned by Utah Associated Municipal Power Systems and operated by Energy Northwest in Idaho, is likely to be the first NuScale implementation.
- A submission of a Construction and Operating License (COL) Application by NuScale's first customer(s) is expected in 2019.
- NuScale expects the first unit to be operating in 2026 and the DOE has granted permission to site the plant on the Idaho National Laboratory estate.

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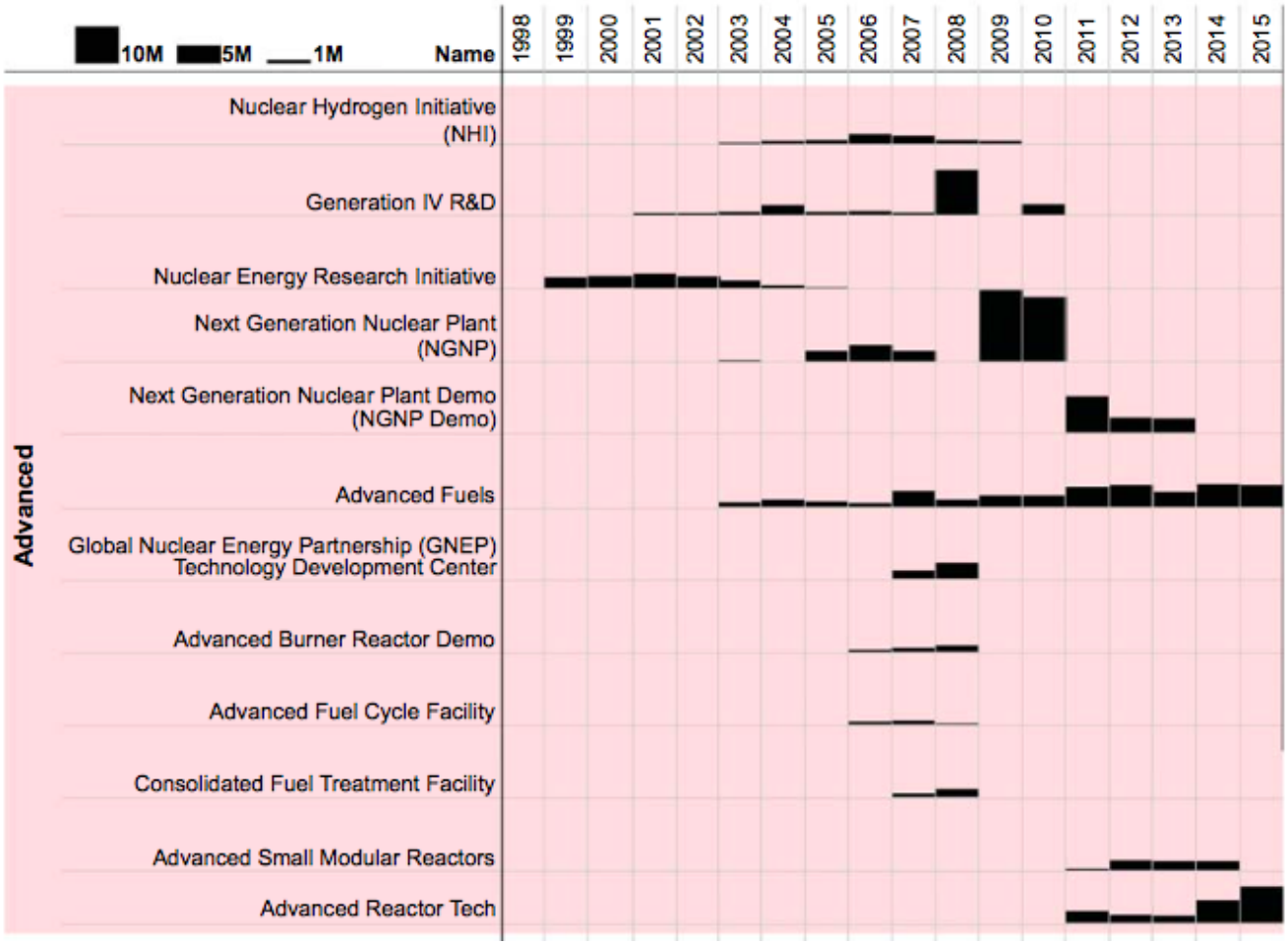
USA – Advanced Nuclear R&D Gov't Spending



A Abdulla *et al* 2017 *Environ. Res. Lett.* **12** 084016

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China - Details

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CHINA – FAST REACTORS

China is currently running three fast reactor development programs:

1. The CFR (Chinese Fast Reactor) sodium-cooled fast reactors
2. The TWR (Travelling Wave Reactor) development in collaboration with TerraPower LLC
3. The CLEAR & CiADS programs on lead/LBE cooled reactors coupled to particle accelerators.

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CHINA – CFR (Chinese Fast Reactor)

- The CFR sodium cooled fast reactor program is, alongside HTR program, the main Gen-IV reactor program in China.
- The Chinese Experimental Fast Reactor (CEFR), built by Russia, has been in operation since 2010/11 and is the main R&D facility for CFR development.
- A 600MWe demonstration plant (CFR600) is currently under construction at Xiapu, in the Fujian province.
- The investment decision for the 1000-1200MWe CFR-1000 is due in 2020, with construction starting in December 2028 and operations scheduled for 2034.

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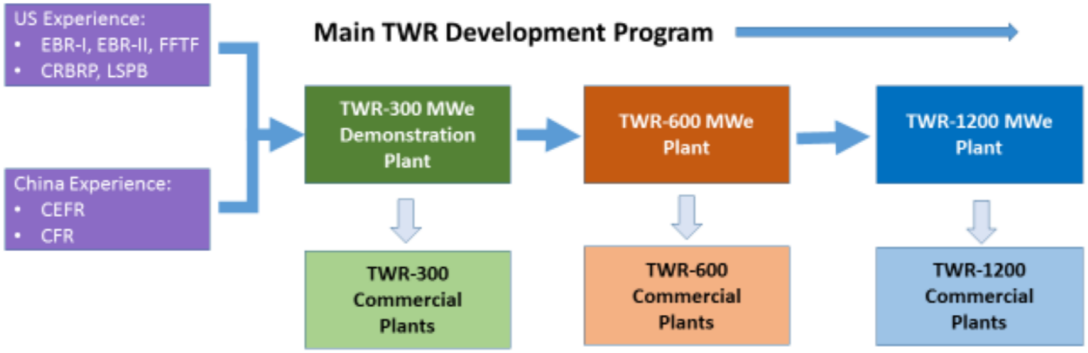
CHINA/US – Traveling Wave Reactors

- In October 2017, TerraPower LLC of the US signed a joint venture with China National Nuclear Corporation (CNNC) to to commercialize TWR technology.
- The CNNC Hebei Nuclear Power has been set up by CNNC with a registered capital of $150m to build and operate TWRs in China.
- The first step is the 300 MWe (TWR-300) demonstration plant, slated for construction start in 2020 and full-power operation by the start of 2025.
- Following the TWR-300, TerraPower & its Chinese partners aim to demonstrate and commercialize the larger TWR-600 (600 MWe) and TWR-1200 (1200 MWe) reactor plants.



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CHINA – HIGH TEMPERATURE REACTORS

- China is moving towards using high-temperature nuclear power plants as an *industrial heat source* and as a direct replacement for coal power plants

- The HTR-10 reactor, an advanced 10 MWt prototype, has been in operation since 2003. The construction of the 2x250 MWt (210 MWe) larger demonstration plant HTR-PM is nearing completion and will be in operation this year.

- Using the HTR-PM as a base, China is developing a scaled-up plant called HTR-PM600, which uses one large turbine rated at 650 MWe driven by six HTR-PM reactor units.

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THE HTR-PM DEMONSTRATION REACTOR

- The HTR-PM in Shidao Bay, Shandong Province, is expected to be connected to the grid and start electricity generation this year.
- The reactor coolant outlet temperature is 750°C, and it will produce steam at 567°C. The very high temperatures means electricity production is highly efficient (42%), and also enables the potential for high-temperature *industrial process heat supply*.
- The HTR-PM demonstration plant cost $6000/kW. A cost reduction to $4500/kW is expected for the first HTR-PM600 units, while for "Nth of a kind" commercial units the near-term cost target is $2400/kW.
- The performance of HTR-PM will determine the future direction of Chinese advanced nuclear.

GRAPHITE PEBBLES (MODERATOR) BEING LOADED AT HTR-PM, APRIL 2017

HTR-PM VESSEL HEAD INSTALLED, DECEMBER 2017

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India - Details

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INDIA – FAST REACTORS

- India has been operating its small Fast Breeder Test Reactor (FBTR) since 1985 as its main R&D facility for advanced reactors.
- The main development project is the 500 MWe Prototype Fast Breeder Reactor (PFBR), a commercial prototype sodium cooled fast reactor.
- All the construction activities were completed in early 2017 and the reactor has since undergone integrated commissioning activities and tests, it is expected to be in operation by March 2018.
- India plans to eventually construct several more new-generation (FBR 600 MWe) with improved economy and enhanced safety beyond PFBR as a part of future FBR programme

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INDIA – Prototype Fast Breeder Reactor

THE PFBR REACTOR AT KALPAKKAM, INDIA

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